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Bio-fuels from thermochemical conversion of renewable resources: A review

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Abstract

Demand for energy and its resources, is increasing every day due to the rapid outgrowth of population and urbanization. As the major conventional energy resources like coal, petroleum and natural gas are at the verge of getting extinct, biomass can be considered as one of the promising environment friendly renewable energy options. Different thermo-chemical conversion processes that include combustion, gasification, liquefaction, hydrogenation and pyrolysis, have been used to convert the biomass into various energy products.

Although pyrolysis is still under developing stage but during current energy scenario, pyrolysis has received special attention as it can convert biomass directly into solid, liquid and gaseous products by thermal decomposition of biomass in absence of oxygen. In this review article, the focus has been made on pyrolysis while other conventional processes have been discussed in brief. For having better insight, various types of pyrolysis processes have been discussed in detail including slow, fast, flash and catalytic pyrolysis processes. Besides biomass resources and constituents, the composition and uses of pyrolysis products have been discussed in detail.

This review article aim to focus on various operational parameters, viz. temperature and particle size of biomass and product yields using various types of biomasses.

Keywords: Biomass; Thermo-chemical; Pyrolysis

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Contents

1. Introduction

Demand for energy and its resources, is increasing continuously due to the rapid outgrowth of population and urbanization. Present sources of energy are not sufficient to overcome the increasing needs. Since 1973 the energy resources have been doubled in developed countries but the demand is still higher.

World energy demand is expected to increase approximately 50% above 2002 level and will increase approximately two and half times the present level.

The major energy demand is fulfilled from the conventional energy resources like coal, petroleum and natural gas. These sources are in the verge of getting extinct. It was estimated that the oil sources might be depleted till 2050.

The process of obtaining energy from these sources causes atmospheric pollution, resulting in problems like global warming, acid rain, etc. Viewing the increase in the energy demands and keeping in view of the pollution a shift over to non-conventional sources like wind, sunlight, water, biomass, etc., is inevitable.

Biomass is being used from the ancient times as a combustion fuel for cooking, keeping warmth in houses, etc. Biomass is available in abundance and is cheap and its better utilization is to convert it to energy rich products using suitable processes.

2. Biomass

2.1. Definition

Biomass is anything living matter on earth. These are the substances in which solar energy is stored. Plants produce biomass continuously by the process of photosynthesis [1–3].

2.2. Resources

Biomass resources can be divided into two broad categories, i.e., natural and derived materials. Biomass resources include wood and wood wastes, agricultural crops and their waste by-products, municipal solid waste, animal wastes, waste from food processing and aquatic plants and algae. Biomass resource can be subdivided into three categories [2,4]: *Wastes*: Agricultural production wastes, agricultural processing wastes, crop residues, mill wood wastes, urban wood-wastes, urban organic wastes.

Forest products: Wood, logging residues, trees, shrubs and wood residues, sawdust, bark, etc., from forest clearings.

Energy crops: Short rotation woody crops, herbaceous woody crops, grasses, starch crops (corn, wheat and barley), sugar crops (cane and beet), oilseed crops (soyabean, sunflower, safflower).

2.3. Biomass constituents

Utility of biomass as feedstock for conversion depends upon the chemical constituents and physical properties. Biomass contains varying amounts of cellulose, hemi-cellulose and lignin.

Cellulose is a polymer, consisting of linear chains of 1, 4-D-glucopyranose units, in which the units are linked 1–4 in the alpha-configuration, with an average molecular weight of around 100,000.

Hemi-celluloses are complex polysaccharides present in the cell wall, which consist of branched structures and vary with biomasses. It is a mixture of polysaccharides, composed almost entirely of sugars such as glucose, mannose, xylose and arabinose and methlyglucoronic and galaturonic acids, with an average molecular weight of $<30{,}000$.

Lignins are highly branched, substituted, mononuclear aromatic polymers in the cell walls of the certain biomass, especially woody species, and are often adjacent to cellulose fibers to form a ligno- cellulosic complex [5]. Lignin is regarded as a group of amorphous, high molecular weight, chemically related compounds. The building blocks of lignin are believed to be a three-carbon chain attached to rings of six carbon atoms, called phenyl-propanes.

In biomass, cellulose is generally the largest fraction followed by hemi-cellulose, lignin, ash, etc. [6,7].

3. Biomass conversion processes

Biomass can be converted to useful products by two main processes:

(a) Thermo-chemical processes
(b) Bio-chemical processes

4. Thermo-chemical processes

The thermo-chemical conversion processes have two basic approaches. The first is the gasification of biomass and its conversion to hydrocarbons. The second approach is to liquefy biomass directly by high-temperature pyrolysis, high-pressure liquefaction, ultra-pyrolysis, or supercritical extraction. These processes convert the waste biomass into energy rich useful products. Choice of conversion process depends upon the type and quantity of biomass feedstock, the desired form of the energy, i.e., end use requirements, environmental standards, economic conditions and project specific factors.

Different thermo-chemical conversion processes include combustion, gasification, liquefaction, hydrogenation and pyrolysis. Although pyrolysis is still under developing stage but during current energy scenario, pyrolysis has received special attention as it can convert biomass directly into solid, liquid and gaseous products by thermal decomposition of biomass in the absence of oxygen. Pyrolysis offers efficient utilization of particular importance for agriculture countries with vastly available biomass by-products. In this article, the focus has been made on pyrolysis while other conventional processes have been discussed in brief as follows:

4.1. Combustion

The biomass is directly burnt in the presence of air to convert chemical energy stored in biomass into heat, mechanical power, or electricity, etc. It is possible to burn any type of biomass but in practice combustion is feasible only for biomass with moisture content of $<50\%$. Combustion process has got many disadvantages. Biomass rarely arises naturally in an acceptable form of burning. In most of the cases it requires some pretreatment like drying, chopping, grinding, etc., which in turn is associated with financial costs and energy expenditure [8,9].

4.2. Gasification

In this process, biomass is converted into a combustible gas mixture by the partial oxidation of biomass at high temperature, in the range 800–900 °C. The biomass is heated in insufficient supply of air. The reactions are as follows [2–4,10]:

$$C + O_2 \longrightarrow CO_2,$$

$$C + \tfrac{1}{2}O_2 \longrightarrow CO,$$

$$CO + \tfrac{1}{2}O_2 \longrightarrow CO_2,$$

$$CO_2 + C \rightleftarrows 2CO.$$

Methane and hydrogen are also formed simultaneously by thermal splitting of organic material.

$$CO_2 + 4H_2 \longrightarrow CH_4 + 2H_2O.$$

4.3. Liquefaction

In this process, liquid is obtained by thermo-chemical conversion at low temperature and high pressure using a catalyst in the presence of hydrogen. It is an expensive process and also the product is a tarry lump, which is difficult to handle [2,11].

4.4. Hydrogenation

This process is mainly for the production of methane by hydro-gasification, i.e., first the syn-gas is formed and then CO is reacted with H_2 to form methane [10].

4.5. Pyrolysis

It is thermo-chemical conversion process and is found to be best suited for conversion of biomass to liquid fuel. Pyrolysis is thermal destruction of biomass in the absence of air/oxygen. Pyrolysis of biomass starts at 350–550 °C and goes up to 700 °C. This leads to the production of useful liquid oil, gases and solid products. Different condition leads to formation of products in different proportions.

4.5.1. Pyrolysis process types

4.5.1.1. Slow pyrolysis. Biomass is pyrolysed at slow heating rates (5–7 K/min). This leads to less liquid and gaseous product and more of char production. Significant amount of work has been done on this process.

Zendersons et al. (1999, Japan, Latvia) conducted slow pyrolysis of sugarcane bagasse for char production and obtained 23–28% yield of charcoal.

Putun et al. ([12], Turkey) conducted fixed bed pyrolysis of Euphorbia rigida, sunflower presses bagasse and hazelnut shell, at different temperatures and heating rate of 7 K/min. Product yield was found to increase in all the three cases when the pyrolysis temperature was increased from 673 to 973 K. Similar results (Table 1) were obtained on increasing the N_2 flow rate [12].

Slow pyrolysis of cottonseed cake at heating rates of 7 °C/min in a tubular reactor was reported by Ozbay et al. ([13], Turkey). Pyrolysis experiments were conducted in two reactors, Heinz retort and a well-swept tubular reactor. From results (Table 2) it was seen that with the increase in the temperature the oil yield increased up to 600 °C but decreased at around 750 °C. Char yield showed continuous decrease. Oil yield was maximum at N_2 flow rate of 100 cm^3/min [13].

Onay and Kockar [14] conducted slow pyrolysis experiments of rapeseed in a Heinz retort and a tubular reactor with variable temperature, nitrogen flows and particle sizes. Results (Table 3) showed that the increase in temperature increased the oil yield up to 550 °C and later reduced beyond this temperature. The char yield decreased and gas yield increased with rising temperature. For particle size $0.6<dp<0$, 85 the oil yield was maximum. Char was found to be the least with the size of $0.85<dp<1.25$.

Fixed bed slow pyrolysis experiments of safflower seed with heating rates of 5 °C/min were reported by Beis et al. (2002, Turkey). Pyrolysis final temperature, sweep gas flow and particle size were the variable parameters during the study. Results showed that oil yield was highest at 550 °C for all particle sizes and flow rates. Gas yield was also found highest at 700 °C. In all the cases the char yield decreases with increase in the temperature.

Table 1
Percent yields of products (approx.) from various biomass at different temperatures [12]

Temp. (K)	Product yield (%)		
	Char	Oil	Water
Euphorbia rigida			
673	44	24	13
773	28	32	17
973	21	26	13
Sunflower			
673	35	36	12
773	27	44	12
973	26	38	12
Hazelnut shell			
673	47	20	14
773	41	23	14
973	36	21	14

Table 2
Variation of product with temperature for cottonseed cake [13]

S. No.	Temp. (°C)	Product yield (%)		
		Char	Oil	Water
1	300	31.0	21.0	26.9
2	350	29.0	21.8	26.0
3	450	28.0	23.2	22.1
4	550	27.0	24.5	23.0
5	650	24.5	23.0	24.0

Table 3
Product yield varying with temperature and particle size [14]

Parameter	Char	Oil	Gas
Temp. (°C)			
400	24	42	26
500	22	46	25
600	19	47	27
700	18	44	31
Particle size			
dp < 0, 425	23	44	26
0.425 < dp < 0.6	22	45	26
0.6 < dp < 0.85	17	48	28
0.85 < dp < 1.25	16	49	29
1.25 < dp < 1.8	17	48	28

Fixed bed pyrolysis studies of sugarcane bagasse, *Calotropis procera* and *Jatropha curcas* seed cake (expelled and extracted) are being continued in the authors' laboratory. Particle size ($-6+8$, $-8+12$, $-12+16$ and -16), temperature (400–600 °C) and N_2 flow (50, 100, 150 and 200 ml/min) were the different variables during the studies. Results indicated that for sugarcane bagasse, maximum oil yield (28.6%) was with $-8+12$ size, at a pyrolysis temperature of 550 °C and with a N_2 purge gas flow of 100 ml/min. In case of *Calotropis Procera*, maximum oil yield (17.7%) was found with mesh size of -16, at a temperature of 460 °C and with a purge gas flow of 150 ml/min. Jatropha curcas seed cake studies are in the progress.

4.5.1.2. Fast pyrolysis. Initially pyrolysis was done with slow heating rates. This in turn produces more of char. The higher yield of desirable liquid product can be obtained by fast pyrolysis. It involves rapid heating of biomass but not as fast as flash pyrolysis. Heating rate is somewhere about 300 °C/min. Generally, fast pyrolysis is used to obtain high-grade bio oil. Fast pyrolysis is successful with most of fluidized bed reactors as it offers high heating rates, rapid de-volatilization, easy control, easy product collection, etc. [15].

Various reactors like entrained flow reactor, wire mesh reactor, vacuum furnace reactor, vortex reactor, rotating reactor, circulating fluidized bed reactor, etc. were designated for performing fast pyrolysis. Many researchers have contributed in the field of fast pyrolysis of biomass using various reactors.

Onay et al. ([16], Turkey) had reported fast pyrolysis of rapeseed in a well-swept fixed bed reactor. Oil yield was obtained as 68% with pyrolysis temperature of 550 °C, particle size 0.6–0.85 mm, heating rate of 300 °C/min and N_2 flow of 100 cm^3/min.

In another experiment, Onay and Kockar [17] conducted experiments on fast pyrolysis of rapeseed to investigate the affect of temperature, heating rate, particle size, and sweep gas flow on the product yield. From the data (Table 4) it was concluded that char yield decreased from 27% to 14.5% with the increase in the temperature. Maximum oil yield of 73% was obtained at temperature of 550–600 °C, particle size of +0.6–1.25 mm, and sweep gas flow rate of 100 cm^3/min.

Luo et al. ([15], China), produced bio-oils by fast pyrolysis of wood stock such as *Pterocarpus indicus, Cunninghania lanceolata* and *Franxinus manshurica* and rice straw. Results (Table 5) show that the yield with *P. indicus* is highest and is lowest for rice straw [18].

4.5.1.3. Flash pyrolysis. Flash pyrolysis is the process in which the reaction time is of only several seconds or even less. The heating rate is very high. This requires special reactor configuration in which biomass residence times are only of few seconds. Two of appropriate designs are entrained flow reactor and the fluidized bed reactor. Flash pyrolysis of any kind of biomass requires rapid heating and therefore the particle size should be fairly small, i.e., approximately 105–250 μm ($-60+140$ mesh size) [19].

Flash pyrolysis is of following types:

(a) *Flash hydro-pyrolysis*: Hydro-pyrolysis is flash pyrolysis done in hydrogen atmosphere. It is carried out at a pressure up to 20 Mpa [19].
(b) *Rapid thermal process*: It is a particular heat transfer process with very short heat residence times (between 30 ms and 1.5 s). It is done at temperatures between 400 and 950 °C. Rapid de-polymerization and cracking of feed stocks takes place. Rapid

Table 4
Percent yield (approx.) with variable particle size and temperature [17]

Parameter	Oil	Char	Gas
Particle size			
dp < 0.425	42.5	22.5	26.2
0.425 < dp < 0.6	45.0	20.0	26.4
0.6 < dp < 0.85	47.5	17.5	27.2
0.85 < dp < 1.25	50.0	16.0	29.2
1.25 < dp < 1.8	47.5	17.5	27.2
dp > 1.8	47.5	22.5	27.2
Temp. (°C)			
400	38	28	< 5
500	60	20	< 5
550	62	19	< 5
600	60	18	< 5
700	59	18	< 5

Table 5
Effect of biomass species on bio-oil production [18]

Biomass	Temp. (K)	Particle size (μm)	Yield	Heating value (kJ/kg)	Water
F. mandshurica	823	74,154	40.2	22,000	39.6
C. lanceolata	773	74,154	53.9	19,000	31.4
P. indicus	773	2,50,355	55.7	19,000	24.6
Rice straw	773	1,54,250	33.7	19,000	53.5

heating eliminates the side reactions whereby giving products with comparable viscosity to diesel oil [20].

(c) *Solar flash pyrolysis*: Concentrated solar radiation can be used to perform flash pyrolysis. The solar energy can be obtained through devices like solar towers, dish connectors, solar furnaces, etc.
Jaques Lede and Oliver Bouten (1999) reported solar flash pyrolysis of samples of cellulose [21].

(d) *Vacuum flash pyrolysis*: In this process, pyrolysis is done under vacuum. It limits the secondary decomposition reactions, which in turn gives high oil yield and low gas yield.

The vacuum facilitates the removal of the condensable products from the hot reaction zone. This prevents further cracking and further re-condensation reactions.

Roy et al. (1999, Canada) reported vacuum pyrolysis of carboniferous age oil shales [22].

Many researchers have used flash pyrolysis process to increase the liquid and the gaseous products.

Horne and Williams (1996, UK) had reported flash pyrolysis of mixed wood waste in a fluidized bed reactor. The reactions were performed at temperature 400, 450, 500, and 550 °C. Influence on product yield was also reported (Table 6).

Table 6
Product yield with temperature from flash pyrolysis of wood [23]

Temp. (°C)	Char (wt%)	Liquid (wt%)	Gases (wt%)
400	24.1	65.5	10.2
450	21.4	65.7	11.1
500	18.9	66.0	14.6
550	17.3	67.0	14.9
550	16.7	67.8	15.7
550	17.1	66.2	15.2

Table 7
Pyrolysis of Aspen Poplar under variable conditions [24]

Poplar Aspen saw dust 105–250 μm						
Run#	4	6	7	14	15	2
N_2 flow rate (ml/min)	800	600	400	400	200	800
Temp. (°C)	545	547	547	548	551	555
Product yield (% of wood fed)						
Char	11.3	9.9	9.7	9.1	9.1	—
Tar	57.5	57.5	51.7	51.7	50.0	45.2
Gas	9.6	13.6	11.9	11.9	16.9	13.1

It was seen that liquid increased marginally where as significant increase in gas yield was observed. Char quantity decreased, as the temperature is increased [23].

Scott and Piskorz (1982, 1984, Ontario) had reported flash pyrolysis of Aspen Poplar wood. Results (Table 7) with different operating conditions were also reported [24].

Experiments on Maple, Aspen Poplar and Wheat straw were also conducted. Results (Table 8) show that liquid and gas yield in all the cases with increase in temperature. Amount of char decreased in all the three cases [25].

Onay and Kockar conducted (2003, Turkey) flash pyrolysis of rapeseed at 550–600 °C with particle sizes +0.6–1.25 mm and N_2 flow of 100 cm^3/min. The data (Table 9) show that the oil yield increased whereas the char quantity decreased with the increase in the temperature [17].

Scott and Radlein (1985, Ontario) performed flash pyrolysis of different biomass samples like maple, Polar bark, Bagasse, Peat, Wheat Straw, Corn Shover and Commercial Cellulose [26].

Maggi and Delmon (1994, Belgium) have done the comparison study of oil obtained from slow and flash pyrolysis of different biomass species [27].

4.5.1.4. Catalytic biomass pyrolysis. From literature it was seen that liquids obtained from biomass by slow, flash or fast pyrolysis process, could not be directly used as transportation fuel. This oil needs to be upgraded as they have high oxygen and water content. These oils are also found to be less stable and less miscible in conventional fuels. Catalytic biomass pyrolysis is introduced to improve the quality of the oil produced.

Table 8
Pilot plant results of Maple, Aspen Poplar and Wheat straw [25]

Temp. (°C)	Product yield (%)			
	Gas	Liquid	Char	Water
Maple				
482	8.42	60.63	20.90	6.3
500	10.27	64.68	12.61	8.2
532	12.05	56.25	9.02	7.8
Poplar Aspen				
425	5.95	55.88	30.59	3.8
465	8.53	67.17	18.88	5.5
500	12.07	71.15	11.2	6.6
541	21.22	63.65	8.99	7.4
Wheat straw				
500	18.92	43.04	23.66	13.22
525	8.63	44.98	24.17	8.66
575	23.24	47.61	17.30	3.92

Table 9
Percent yield of pyrolysis product with temperature and particle size [17]

Parameter	Oil	Char	Gas
Particle size			
dp < 0.425	55.0	20	19.0
0.425 < dp < 0.6	58.0	20	17.0
0.6 < dp < 0.85	68.0	15	15.0
0.85 < dp < 1.25	67.0	16	15.5
1.25 < dp < 1.8	66.0	16	16.0
dp > 1.8	65.0	17	17.0
Temp. (°C)			
400	56.3	33.3	< 10
500	70.0	16.3	< 10
550	70.1	16.3	< 10
600	71.15	16.0	< 10
700	66.31	16.0	13.3

The oil obtained by catalytic biomass pyrolysis does not require costly pre-upgradation techniques involving condensation and reevaporation. Various catalysts such as zeolites and basic materials were introduced with the biomass feed stock [28].

Somaloda et al. (2000, Greece) performed catalytic biomass pyrolysis using catalysts like pure zeolite (A: HZSM-5), FCC catalysts (FCC, B: Re USY), aluminas (alpha, gamma-Al_2O_3) and transition metal catalysts (Fe/Cr).

From the replicate runs with different catalysts 80–99% wt% mass balances were obtained [28].

Catalytic pyrolysis of rice husk was reported by Williams and Nugranad (2000, UK). Pyrolysis was done at temperature 400, 450, 500, 550 and 600 °C using ZSM-5 catalyst [29].

4.5.2. Pyrolysis reactors

Pyrolysis reactor designs includes fixed beds, moving beds, suspended and fluidized beds, entrained feed solid reactor, inclined rotating kilns, etc. Some of the reactors used consists of circulating fluid bed reactor, ablative pyrolysis reactor, bubbling fluid bed reactor, rotating cone reactor, vacuum pyrolysis reactor, wire mesh reactor, ultra pyrolysis entrained flow reactor, etc.

5. Pyrolysis product composition

5.1. Pyrolysis oil composition

Oil obtained from the pyrolysis of biomass contains several organic as well as inorganic species. Some of the organic groups present in the bio-oil are mentioned below:

- *Acids*: Formic, acetic, propanoic, hexanoic, benzoic, etc.
- *Esters*: Methyl formate, methyl propionate, butyrolactone, methyl *n*-butyrate, velerolactone, etc.
- *Alcohols*: Methanol, ethanol, 2-propene-1-ol, isobutanol, etc.
- *Ketones*: Acetone, 2-butanone, 2-butanone, 2-pentanone, 2-cyclopentanone, 2,3 pentenedione, 2-hexanone, cyclo-hexanone, etc.
- *Aldehydes*: Formaldehyde, acetaldehyde, 2-butenal, pentanal, ethanedial, etc.
- *Phenols*: Phenol, methyl substituted phenols.
- *Alkenes*: 2-methyl propene, dimethylcyclopentene, alpha-pinene, etc., Aromatics: Benzene, toluene, xylenes, nphthalenes, phenanthrene, fluoranthrene, chrysene, etc.
- *Nitrogen compounds*: Ammonia, methylamine, pyridine, methylpyridine, etc.
- *Furans*: Furan, 2-methyl furan, 2-furanone, furfural, furfural alcohol, etc.
- *Guaiacols*: 2-methoxy phenol, 4-methyl guaiacol, ethyl guaiacol, eugenol, etc.
- *Syringols*: Methyl syringol, 4-ethyl syringol, propyl syringol, etc.
- *Sugars*: Levoglucosan, glucose, fructose, D-xylose, D-arabinose, etc.
- *Miscellaneous oxygenates*: Hydroxyacetaldehyde, hydroxyacetone, dimethyl acetal, acetal, methyl cyclopentenolone, etc. [30–31].

Inorganics species are present in following forms in the bio-oil:

(i) Associated with counter ions.
(ii) Connected to organic acids.
(iii) Related to various enzymatic compounds.

Inorganics present in the bio oil comprises of Ca, Si, K, Fe, Al, Na, S, P Mg, Ni, Cr, Zn, Li, Ti, Mn, Ln, Ba, V, Cl, etc. [30–31].

5.2. Pyrolysis gas composition

Pyrolysis gas comprises of CO, CO_2 and CH_4. The other components present are H_2, propane, propylene, butane, butenes, C_5, ethane, etc.

5.3. Pyrolysis char composition

Char contains elemental carbon along with hydrogen. In addition, char also comprises various inorganic species.

6. Pyrolysis products application

6.1. Uses of bio-oil

The bio-oil obtained from pyrolysis can have the following industrial uses:

- combustion fuel,
- used for power generation,
- production of chemicals and resins,
- can be used as a transportation fuel and could be a good substitute for fossil fuels,
- can be used as liquid smoke,
- production of anhydro-sugars like levoglucosan,
- used as binders for palletizing and briquetting of combustible organic waste materials,
- bio-oil can be used as preservatives, e.g., wood preservative,
- a suitable blend of a pyrolysis liquid with the diesel oil may be used as diesel engine fuels,
- bio-oils can be used in making adhesives,
- the oil obtained from sewage sludge pyrolysis can be used directly in diesel fuelled engines,
- the oil may be stored and transported, and hence need not to be used at the production site.

6.2. Uses of char

The char can be utilized for various industrial usages which are discussed as follows [32]:

- The char could be used as a solid fuel in boilers where bagasse or other biomass is presently burnt. This can be converted into brickets alone or mixed with biomass and can be used as high efficiency fuel in boilers.
- The char could be used for the production of activated carbon.
- Possibility of using this carbon feedstock for making carbon-nano-tubes may be explored.
- It can be used futher for the gasification process to obtain hydrogen rich gas by thermal cracking.

6.3. Uses of gas

Pyrolysis gas containing significant amount of carbon dioxide along with methane, might be used as a fuel for industrial combustion purposes.

7. Conclusions

It is necessary to get a process which can convert biomass into useful energy products especially to liquids which can be a good substitute for the depleting fossil

fuels.Thermochemical conversion methods are the best suited to achieve the requirement as these are ecofriendly processes. Pyrolysis has received a significant amount of interest as this gives products of better quality compared to any other thermochemical process. From literature it can be concluded that slow pyrolysis which is done at a slow heating rate, yields more of the char. It was also seen that in some of the cases oil yield though goes on increasing with temperature but decreases after a certain increase in the pyrolysis temperature. Compared to this the fast and the flash pyrolysis processes are found to be good substitutes whereby the oil yield is comparatively high. Catalytic biomass pyrolysis which is another way to upgrade the quality of the products, is also a process of interest. It may also be apllied to improve the quantiity and the quality of the gaseous products to make it more useful for obtaining energy through combustion. Authors of this review may conclude that the pyrolysis, which is thermochemical conversion process may become an important process for obtaining energy from biomass and could be a process of extreme importance for the developing nations like India.

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